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THE TRANSMISSION OF RÖNTGEN RAYS THROUGH METALLIC SHEETS.

BY JOHN MEAD ADAMS.

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By John Mead Adams.

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I. Introduction.

This experimental investigation into the phenomena of the transmission of Röntgen rays through metallic sheets has grown out of a research which was undertaken three years ago for the purpose of confirming the measurements of the energy of Röntgen rays then recently made by Dorn,[1] Rutherford and McClung,[2] Schöps,[3] and others. These measurements had been rendered somewhat doubtful by Leininger's[4] unsuccessful attempt to repeat the work of Rutherford and McClung and of Schöps, and it seemed desirable to obtain new evidence on the question by a method different from those already used.

In general plan the methods of the above-mentioned investigators were similar. Each of them allowed the rays to fall upon thin sheets of metal, and from the heat developed in the metal estimated the energy of the absorbed rays; then, after making a correction for the fact that not all of the rays incident on the metal are absorbed in it, they were able to calculate the rate at which the tube was radiating energy in the form of Röntgen rays, by assuming from the work of Röntgen[5] and of Guillaume[6] that the emission of energy is nearly uniform in all directions from the target. To reduce the results to absolute measure, it was only necessary to send through the absorbing metal a known electric current of such strength that the heating effect thereby produced was equal to that produced by the absorption of the rays; the Joulean heat of the current in the metal was then taken to be equal to the energy of the absorbed rays. The methods differed in

[1] E. Dorn, Ann. d. Phys., **63**, 160 (1897).
[2] E. Rutherford and R. K. McClung, Proc. Roy. Soc., **67**, 245 (1900).
[3] Schöps, Zeitsch. für Naturwiss., **72**, 145 (1899).
[4] F. Leininger, Phys. Zeitsch., **2**, 692 (1901).
[5] W. C. Röntgen, Ann. d. Phys., **64**, 22 (1898).
[6] Ch.-Ed. Guillaume, Comptes Rendus, **123**, 450 (1896).

the means used to detect the heat developed in the metal. Dorn immersed the metal in a body of gas; the rise of temperature of the gas, due chiefly to the heat produced in the metal, caused a corresponding rise of pressure, which was made evident upon a delicate pressure-balance. Rutherford and McClung and Schöps, and Leininger following them, made the metal the sensitive arm of a bolometer. The methods differed also in the correction for the incomplete absorption of the rays. Dorn arranged his apparatus so that the rays had to pass through several layers of the metal, and thus were almost completely absorbed. The others observed the diminution of heating effect which occurred when a piece of metal, of the same kind and thickness as the absorbing sheet, was interposed between the latter and the tube, and hence estimated what fraction of the rays was effective in producing heat.

The method followed throughout the present research was a modification of this general plan. A Boys' radiomicrometer [7] was the instrument used, the thin piece of metal which partially absorbed the rays being placed at one of the junctions of the thermal couple. With this instrument, which is described in detail below, a heating effect was readily perceived; and some measurements were made of the whole energy of the Röntgen rays emitted per second by a tube, which measurements are included in this paper as a confirmation of the results obtained by the earlier investigators.

In the course of this work it became plain that there is at least one possible source of error which may affect, more or less, all measurements of the energy of Röntgen rays based upon observations of the heat developed by the absorption of the rays in thin metallic sheets. The well-known fact that the character of Röntgen radiation is changed by passage through solid substances shows that the methods thus far used to correct for the imperfect absorption of such sheets may yield only a first approximation to the truth. This uncertainty as to the exact effect produced upon a beam of Röntgen rays by passage through metallic sheets suggested the subjects experimentally investigated in this paper. These subjects are:

(1) The effect of varying the thickness of a metallic sheet upon transmission through it.

(2) The effect of varying the intensity of the incident radiation upon transmission through a metallic sheet.

(3) The effect of the surfaces of the sheet upon transmission through it, as distinguished from the effect occurring within its substance.

(4) The effect of transmission through a sheet of one metal upon the penetrating power of the rays for a sheet of another metal.

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[7] C. V. Boys, Phil. Trans., **180**, 159 (1888–1889).

(5) The nature of the effect which occurs within the substance of the sheet.

Most of these subjects had already been investigated by various observers at more or less length, by means of the photographic plate, the fluoroscope, and ionization phenomena; but in view of the semi-qualitative nature of photographic and fluoroscopic work, and considering the difficulty of an exact interpretation of the phenomena of ionization, it seemed desirable to reinvestigate the subjects with a strictly quantitative instrument.

The results obtained confirm the work of earlier investigators in most cases, but in one or two important particulars they are at variance with generally accepted views. It is believed that such measurements as those here published are valuable not only in themselves, but as an indication of the way to a more accurate quantitative examination of the nature of the Röntgen radiation than has yet been made.

II. Apparatus.

Figure 1 illustrates the suspended system of the instrument. It consisted of a loop, L, of copper wire 0.026 cm. in diameter, completed at the lower end by a bit of constantan wire, C, and a thin circular piece of platinum, D. The junctions were made with a soft solder, no acid being used, and all superfluous solder being removed. The wires at the upper end of the loop were twisted together, and carried a light mirror, M. A vertical section through the wooden case of the instrument is shown in Figure 2. The loop of copper was hung by a fine quartz fibre in a magnetic field due to the permanent magnets, N, S. The block of soft iron, I, was drilled horizontally and vertically as represented, and was designed to prevent the magnetic field from exerting a directive force on the suspended system. A copper sheathing, not shown in the section, lined the central cavity of the wooden case throughout its length. The Röntgen rays entered the instrument through a thin aluminium window at A and were partially absorbed in the platinum. The heat thus developed at the lower junction of the copper-constantan couple produced an electric current around the loop, which caused the suspended system to rotate in the magnetic field until brought to rest by the opposing torsion of the fibre. The dimensions of the instrument may be estimated from Figure 2, which is about one third actual size. The thickness of the absorbing platinum was 0.0014 cm., and its diameter 0.38 cm. The thickness of the aluminium window was 0.015 cm. A telescope and scale, the latter 151 cm. from the mirror, were used to read the deflections.

Disturbances of many sorts were encountered and, so far as possible,

avoided in setting up and using this instrument. It was placed on a heavy iron pillar rising from the cement floor of a basement room. The outside of the wooden case was covered with tinfoil, and a partition of roofing tin, 2 m. high by 1.3 m. wide, was placed between the instrument and the tube and was put to earth. A hole 1 cm. in diameter was bored in the partition to give passage to the rays. As

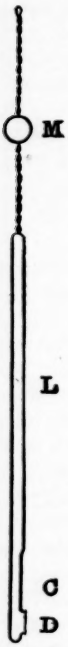

FIGURE 1.

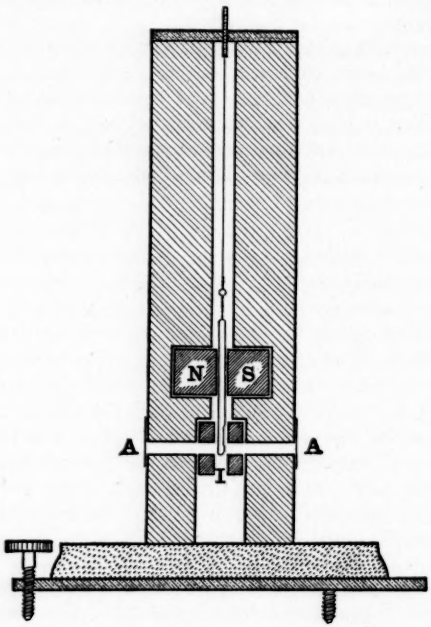

FIGURE 2.

an indication of the efficacy of these precautions against electrostatic disturbance, it may be stated that when powerful sparks were allowed to pass to the partition from the coil used to drive the tube, the zero reading of the instrument was not in the least affected. It seemed that the magnetic field about the suspended system exerted a considerable directive force upon the latter, notwithstanding the soft-iron block, and direct experiments confirmed this belief. In order, therefore, that not only the sensitiveness of the instrument but its zero reading

might be independent of transient changes in the external magnetic field, a hollow cylinder of soft iron, with wall 0.6 cm. thick and with the necessary apertures, was slipped over the case. The effects believed to be due to external magnetic disturbances were thereby much diminished. Changes in the room temperature promptly produced a drift of the zero reading. To avoid this drift as much as possible, the instrument was jacketed with cotton wool and hair felt, the aluminium window for the rays being covered only by a thin layer of the latter, which appeared by the use of the fluoroscope to be perfectly transparent. In addition to this, a double-walled house of asbestos, large enough for a man to enter, was built around the instrument, the partition, and the tube. The aperture for observing the mirror was protected by a water-window about 8 cm. thick, and the telescope and scale were placed outside the asbestos house. These precautions were found sufficient for seasons when there was no artificial heat in the building, but during the winter the interior of the house had to be kept at an approximately constant temperature by means of an electric stove and an automatic regulator. Because of the small mass of the suspended system — one or two tenths of a gram — mechanical vibrations, such as those produced by machinery in neighboring buildings or by a high wind, greatly limited the hours available for work with the instrument.

The tube [8] employed as a source of Röntgen rays was one especially designed for use with a Tesla coil. It is illustrated in section in Figure 3. The Tesla coil was operated with power obtained indirectly from the incandescent lighting mains. From those mains the alternating current (110 volts, 60 cycles per second) was led to the primary of a step-up transformer and an adjustable resistance in series with it. The current from the secondary of this transformer charged a condenser of 0.005 mfd. capacity to a difference of potential of from 5,000 to 10,000 volts. The condenser was connected in series with the primary of the Tesla coil and a Cooper-Hewitt interrupter, and discharged itself through that circuit with a frequency of about 7×10^5 oscillations per second. Under these circumstances a spark from the Tesla secondary 33 cm. long between points was obtained; but for ordinary purposes a spark of half that length proved sufficient. By keeping the interrupter at a constant temperature of from 75° to 90° C., it was found possible to maintain a remarkably uniform activity of the tube for considerable periods, especially in the case of new tubes.

[8] Manufactured by the Macalaster Wiggin Company, Boston.

The distance from the platinum of the instrument to the centre of the target of the tube was 22 cm. in all the experiments described in this paper, with a few exceptions which are noted where they occur. The metallic sheets were interposed in the beam of rays at about 11 cm. from the platinum of the instrument in all cases. Throughout the remainder of this paper these metallic sheets will be referred to as "screens."

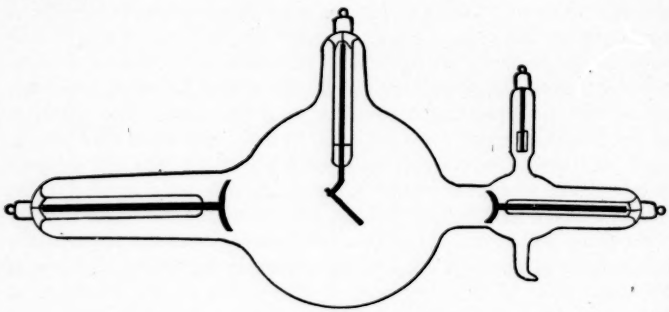

FIGURE 3.

The two electrodes at opposite ends of the bulb were of aluminium, and between them passed the rapidly oscillating discharge from the secondary of the Tesla coil. At the centre of the bulb was fixed the platinum target, upon which the cathode stream from the larger aluminjum electrode came to a focus. In the ordinary use of the tube, the target had no metallic connection with the rest of the system. The effect of the constriction in the walls of the tube in front of the smaller aluminium electrode was to choke off more or less the cathode stream emanating from that electrode. The tube was provided with a device for reducing the vacuum.

III. APPROXIMATE MEASUREMENT OF THE ENERGY.

Soon after the instrument was set up, a test was made to ascertain whether its deflections were proportional to the amount of radiant energy which it absorbed per second at its sensitive surface. For the purpose of this test, and of the calibration described below, the platinum of the instrument had been coated on one side with a thin paste of lamp-black in kerosene. A small battery-lamp using about 5 watts served as a radiating source, and was placed about 3 meters from the instrument, the aluminium window of the latter being raised so as to expose the platinum to the radiation. After noting the zero, the current was sent through the lamp and the maximum deflection read. Then the lamp was moved nearer and another deflection taken, and so

on. The distances used were such that the lamp could be considered as a point source, and hence the constancy of the product

$$\text{deflection} \times \text{square of distance}$$

is proof of the proportionality in question. The maximum deflection was used rather than the steady deflection, in this work and in all the

TABLE I.

RELATION OF DEFLECTION TO ENERGY ABSORBED.

d.	Zero Reading.	Maximum Reading.	Throw, cms.	$d^2 \times$ Throw.
2.90	20.90	21.53	.63	5.30
2.80	20.96	21.64	.68	5.33
2.70	21.01	21.77	.76	5.54
2.60	21.17	21.96	.79	5.34
2.50	21.24	22.11	.87	5.44
2.40	21.36	22.29	.93	5.36
2.30	21.41	22.44	1.03	5.45
2.20	21.50	22.62	1.12	5.42
2.10	21.60	22.83	1.23	5.42
2.00	21.71	23.04	1.33	5.32
1.90	21.80	23.30	1.50	5.42
1.80	21.89	23.57	1.68	5.44
1.70	21.98	23.86	1.88	5.43
1.60	22.03	24.12	2.09	5.35
1.50	22.12	24.52	2.40	5.40
1.40	22.18	24.93	2.75	5.39

work of this paper, because of the drift and other disturbances which rendered inaccurate the determination of the steady deflection. A specimen set of readings is given in Table I. By d is indicated the distance from the lamp to the platinum of the instrument, in meters.

A calibration of the instrument in absolute measure was next made.

As a standard of radiation was chosen the "black body" [9] formed by the small opening of a cavity kept at 100° C. by a steam jacket. At 50 cm. distance this standard radiator, 3.14 sq. cm. in area, produced a deflection of 111 mm., the platinum of the instrument being in the normal to the radiating surface; and by using Kurlbaum's [10] measurement of the total net radiation from such a body to its surroundings at the room temperature (0.0156 gm. cal. per sq. cm. per sec., distributed through the half sphere according to the cosine law), it was computed that a small source 1 meter away, radiating energy according to the cosine law, must emit altogether 0.00177 gm. cal. per sec. to produce a deflection of 1 mm. In other words, a deflection of 1 mm. was produced when the platinum was receiving energy at the rate of 5.63×10^{-8} gm. cal. per sec., per sq. cm. of its surface.

With this result, an approximate measurement of the total energy of the Röntgen rays was readily obtained. The tube was placed so that the centre of the target was 20 cm. from the platinum of the instrument. A screen of platinum 0.0026 cm. thick was arranged so that it could be interposed in the path of the rays or withdrawn at pleasure. (A screen 0.0014 cm. thick, like the platinum used in the instrument, would have simplified the calculation, but none was available.) Then readings of the throws produced by the rays with the screen out were taken, alternating with readings with the screen in. These readings are given in Table II. In each case the rays were kept on until the maximum deflection occurred, a period of about 10 seconds. From the mean deflection obtained when the screen was not interposed, 0.890, the total energy of that portion of the rays which was absorbed was found to be

$$2\pi \times 20^2 \times 8.90 \times 5.63 \times 10^{-8} \text{ gm. cal. per sec.,}$$

or 0.00126 gm. cal. per sec. To find what fraction of the whole radiation this represented, it was assumed [11] that the fraction of rays transmitted by a piece of platinum is given in terms of its thickness, t, by e^{-kt}. Then k was found from

$$\frac{0.274}{0.890} = e^{-0.0026\,k}$$

to be equal to 453. Hence the fraction of the incident rays which the instrument absorbed was

$$1 - e^{-453 \times 0.0014},$$

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[9] Wien and Lummer, Ann. d. Phys., **56**, 451 (1895).

[10] F. Kurlbaum, Ann. d. Phys., **65**, 746 (1898).

[11] This assumption of an exponential absorption law is without justification, and probably in the present case is far from the truth.

or 0.470, and the whole energy of the rays was then $\frac{0.00126}{0.470}$, or 0.00268 gm. cal. per sec. A correction for the absorption in the aluminium window of the instrument, obtained by assuming expo-

TABLE II.

APPROXIMATE MEASUREMENT OF ENERGY.

	Screen out.		Screen in.	
Zero Reading.	Maximum Reading.	Throw, cms.	Maximum Reading.	Throw, cms.
28.47	29.34	0.87		
28.50			28.76	0.26
28.52	29.39	0.87		
28.49			28.76	0.27
28.52	29.39	0.87		
28.51			28.80	0.29
28.52	29.42	0.90		
28.53			28.78	0.25
28.52	29.40	0.88		
28.53			28 81	0.28
28.51	29.41	0.90		
28.53			28.82	0.29
28.55	29.45	0.90		
28.58			28.86	0 28
28.60	29.53	0.93		
Means		0.890	. . . . .	0.274

nential absorption in aluminium, increased this result to 0.00325 gm. cal. per sec.

As a quantitative determination of the energy of Röntgen rays, not too much importance should be attached to this measurement, because the method is subject to obvious inaccuracies, and also because

any measurement of this quantity is of little significance unless accompanied by complete specification of the conditions under which the rays are produced. But as a confirmation of the qualitative result of the earlier investigations, it serves the purpose for which it was undertaken; and, together with the recently published work of Wien,[12] of Bumstead,[13] of Angerer,[14] and of Carter [15] establishes beyond reasonable doubt the fact that the absorption of Röntgen rays in metals is accompanied by the appearance of a measurable amount of heat. It may be of interest, however, to remark that the result reached above is of the same order of magnitude as those found by the other investigators: Dorn's tube yielded an output of 0.00151 to 0.00168 gm. cal. per sec., Rutherford and McClung found 0.011 gm. cal. per sec., Wien has obtained 0.0015 gm. cal. per sec., Angerer gives a maximum value of 0.013 gm. cal. per sec., and Carter finds 0.00514 gm. cal. per sec. In this connection it may be added that in the latter part of the present research rays were used the energy of which was undoubtedly of the order of 0.01 gm. cal. per sec.

IV. Experiments on Transmission.

1. *Change in Transmission accompanying Change in Thickness of Screen.*

The change in transmission which accompanies a change in the thickness of a metallic screen has been examined by many observers, and has been found in every case to follow the same qualitative law, namely, that each succeeding equal increment of thickness is less effective as an absorbing medium than the one preceding it. Experiments made in the course of the present research confirm this law for all the metals examined, and it seems necessary here only to indicate the mode of procedure followed in these experiments, and to give a specimen of the curves obtained.

A series of screens of the metal to be examined was prepared. Each screen was built up to the desired thickness from thin sheets of the metal, — a method which is justified by experiments described below. The screens were then interposed, one by one, in the path of the rays, and the corresponding deflections of the instrument observed. Just before and just after taking each deflection the screens were with-

[12] W. Wien, Ann. d. Phys., **18**, 991 (1905).
[13] H. A. Bumstead, Amer. Jour. Sci., **171**, 1 (1906).
[14] E. Angerer, Ann. d. Phys., **21**, 87 (1906).
[15] E. Carter, Ann. d. Phys., **21**, 955 (1906).

drawn, and the deflection produced by the unimpeded rays was observed, for the purpose of making allowance for any small variation in the activity of the tube. The ratio of each deflection obtained with a screen interposed to the mean of these two standardizing deflections was computed, and the relative deflection thus obtained was plotted as ordinate

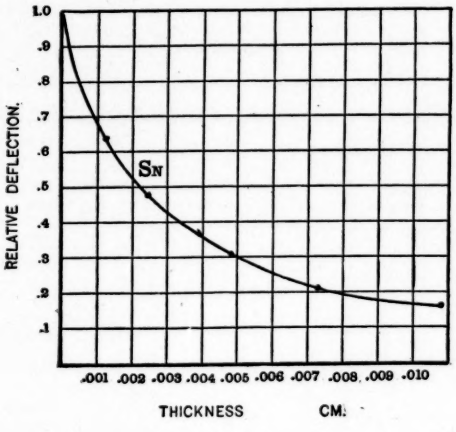

FIGURE 4.

This curve shows the relation between the deflections of the instrument and the thickness of the tinfoil screens interposed in the path of the rays. The thickness, in centimeters, is plotted as abscissa, and the corresponding "relative deflection" (that is, the deflection observed when the screen is interposed divided by the deflection observed when the screen is withdrawn) is plotted as ordinate. It is to be noticed that each successive equal increment of thickness of the screen is less effective in reducing the deflection than the one preceding it.

against the thickness of the corresponding screen as abscissa. An experiment of this kind on screens of tin is illustrated by Figure 4. The tinfoil used was not much alloyed by lead, judging from its appearance and from a measurement of its specific gravity. The curve is from data taken January 9 with the tube at 20 cm. from the instrument. A curve taken January 10, with the tube at 25 cm. distance, and another curve taken on the latter day with the tube at 20 cm. distance, coincide with this one so closely as to be indistinguishable from it. Such exact reproduction of results on successive days was possible only when the tube was comparatively new.

2. *Change in Transmission accompanying Change in Intensity of Incident Radiation.*

The metals used in the following experiments were platinum, 0.0014 cm. thick; copper, 0.0044 cm.; silver, 0.0019 cm.; tin, 0.0012 cm.; aluminium, 0.027 cm. The method was the same in all cases except for differences in detail. The experiment with silver will serve as an example.

TABLE III.

EFFECT OF VARIATION OF INTENSITY UPON TRANSMISSION BY SILVER.

Distance, 42 cms.			Distance, 22 cms.		
Screen out. Throw, cms.	Screen in. Throw, cms.	Ratio.	Screen out. Throw, cms.	Screen in. Throw, cms.	Ratio.
1.62	1.11	0.68			
1.64			5.82	3.98	0.70
			5.61		
1.62	1.11	0.68			
1.60			5.78	3.91	0.67
			5.84		
1.65	1.11	0.67			
1.66			5.92	4.10	0.68
			6.12		
1.77	1.20	0.68			
1.74					
Means		0.678	. . . . .		0.683

The tube was placed as far as convenient from the instrument (42 cm. from the platinum of the latter to the centre of the target), and a "ratio of transmission" was obtained by dividing the deflection taken when the screen was in by the mean of two standardizing deflections taken when the screen was out. Then the tube was moved toward the instrument a distance of 20 cm. along a track which had been carefully aligned with the instrument before the latter was jacketed, and a determination

was made of the ratio of transmission of the silver screen under these circumstances. The screen was interposed at the same place, relatively to the instrument, as before; hence the motion of the tube involved a considerable variation of the intensity of the radiation incident on the screen. The extremes of intensity were in the ratio of 1 to 8 in this experiment, if the law of inverse squares is applicable. The tube was then returned to its original position, and the first ratio of transmission redetermined as a safeguard. By repeating this process several times, the set of readings in Table III was obtained.

TABLE IV.

EFFECT OF VARIATION OF INTENSITY UPON TRANSMISSION BY PLATINUM.

	Screen out. Throw, cms.	Screen in. Throw, cms.	Ratio.	Mean.
Distance, 22 cms.	2.80	1.25	0.43	0.39
	3.05	1.10	0.36	
	3.10	1.20	0.38	
	3.20			
Distance, 42 cms.	0.90	0.30	0.33	0.39
	0.90	0.40	0.42	
	1.00	0.37	0.41	
	0.80			
Distance, 22 cms.	3.00	1.12	0.41	0.39
	2.40	0.85	0.37	
	2.15	0.73	0.39	
	1.60			

The experiment with platinum is of especial interest because of the use made of that metal as the absorbing material of the instrument. Table IV shows the procedure and the result of this experiment.

From the experiments on copper, tin, and aluminium it appeared that for those metals, as for silver and platinum, the ratio of transmission is independent of the intensity of the incident radiation for a considerable range of intensity.

3. *Experiments to show a Possible Effect of the Surfaces of a Screen on Transmission.*

Experiments with two metals, aluminium and copper, were made in order to find evidence of any effect which the *surfaces* of the screen might exert on transmission. The results in both cases were negative. These experiments were conducted in the following way:

A set of screens of different thicknesses was prepared, each screen consisting of a single solid piece of the metal in question. A second

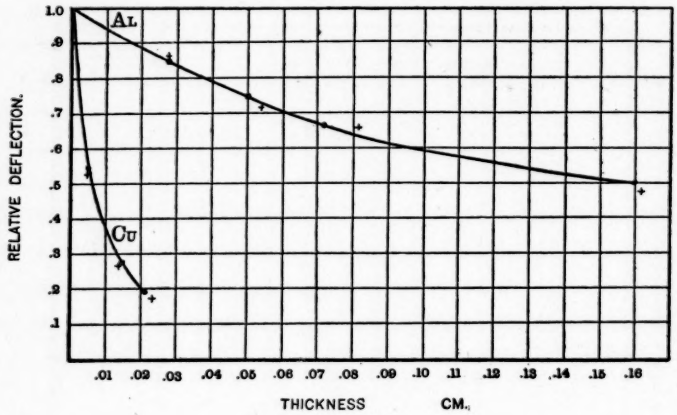

FIGURE 5.

This figure shows the small effect of the *surfaces* of screens upon transmission, in the case of aluminium and of copper. The curves are obtained by plotting as abscissa the thickness of each of a set of one-piece screens of the metal under examination against the corresponding "relative deflection" (that is, the deflection observed when the screen is interposed divided by the deflection observed when the screen is withdrawn) as ordinate. The crosses are points on a curve obtained when laminated screens were substituted for one-piece screens.

set of screens was made, similar to the first except that the screens were laminated. The pieces of metal used were brightly polished on both sides. From the first set of screens a curve was obtained by the method described on page 681. A similar curve was taken for the laminated screens, and lastly, to check the constancy of the tube, a second curve for the solid screens. Readings were taken at intervals of one minute, and in these experiments the rays were not allowed to run until the greatest attainable deflection occurred, but were cut off

TABLE V.

EFFECT OF SURFACES OF ALUMINIUM SCREEN.

	No. of Screen.	Throw, cms., without Screen.	Throw, cms., with Screen.	Ratio.
Data for First Transmission Curve for Solid Screens.	1	1.15	1.06	0.82
	2	1.43	1.10	0.72
	3	1.62	1.09	0.68
	4	1.59	0.73	0.48
	3	1.46	1.01	0.67
	2	1.55	1.13	0.76
	1	1.40	1.14	0.86
		1.24		
Data for Transmission Curve for Laminated Screens.	1	1.24	1.02	0.82
	2	1.23	0.88	0.73
	3	1.16	0.72	0.63
	4	1.12	0.51	0.47
	3	1.05	0.74	0.68
	2	1.13	0.77	0.71
	1	1.05	0.89	0.89
		0.95		
Data for Second Transmission Curve for Solid Screens.	1	0.95	0.80	0.86
	2	0.90	0.69	0.74
	3	0.95	0.64	0.67
	4	0.97	0.49	0.51
	3	0.96	0.59	0.63
	2	0.92	0.70	0.76
	1	0.91	0.77	0.84
		0.92		

by an automatic device after running three seconds. Though this reduced the size of the deflections, it rendered less rapid the change in condition of the tube. The deflections of the instrument under these conditions appear, from considerations of the motion of the suspended system under the forces involved, to be proportional to the energy received during the exposure, just as in the case where the greatest attainable deflection is used.

A comparison of the mean curve for the solid screens with the curve for the laminated screens should show the effect upon transmission, if any, due to the surfaces of the screen. In Figure 5 the dots and the curves drawn through them are from the data obtained with the solid screens; the crosses are points on the curve for the laminated screens. The screens used in the experiment with aluminium were as follows:

Solid screens: No. 1, 0.027 cm. No. 3, 0.072 cm.
No. 2, 0.050 cm. No. 4, 0.160 cm.

Laminated screens: No. 1, 0.027 cm., 1 layer.
No. 2, 0.054 cm., 2 layers.
No. 3, 0.081 cm., 3 layers.
No. 4, 0.162 cm., 6 layers.

Those used in the experiment with copper were:

Solid screens: No. 1, 0.0044 cm. No. 3, 0.021 cm.
No. 2, 0.014 cm.

Laminated screens: No. 1, 0.0044 cm., 1 layer.
No. 2, 0.013 cm., 3 layers.
No. 3, 0.023 cm., 5 layers.

TABLE VI.

SUMMARY OF TABLE V.

Solid Screens.		Laminated Screens.	
Screen No.	Ratio.	Screen No.	Ratio.
1	0.85	1	0.86
2	0.75	2	0.72
3	0.66	3	0.66
4	0.50	4	0.47

Table V contains the data of the experiment with aluminium in full, and in Table VI the mean ratios of transmission for that experiment are collected. Table VII gives the mean ratios of transmission for the experiment with copper. The accuracy of the readings with aluminium was greater than that of the readings with copper, the deflections being larger. It is to be noted, however, in both Table VI and Table VII, that the ratios for solid screens are not strictly comparable with the corresponding ratios for laminated screens, for corresponding screens of the two sets are not quite of the same thickness in most cases. In plotting the curves in Figure 5, this fact is taken into account.

TABLE VII.

SUMMARY OF EXPERIMENT ON EFFECT OF SURFACES OF COPPER SCREEN.

Solid Screens.		Laminated Screens.	
Screen No.	Ratio.	Screen No.	Ratio.
1	0.55	1	0.53
2	0.28	2	0.27
3	0.19	3	0.17

From these results we may conclude that in the case of aluminium and of copper, the effect of the surfaces as such on the transmission of the rays is too small to be detected in measurements of this degree of precision, if it exists at all.

4. *Effect of Transmission through a Screen of One Metal on Penetrating Power for a Screen of Another Metal.*

It has been generally supposed that the transmission of a beam of rays through a screen of any substance renders the beam more penetrating toward another screen of the same or of any other substance than it was originally. In view of the importance of this matter a reexamination of the experimental facts seemed desirable. Accordingly experiments were performed for the purpose of comparing the penetrating power for a given metallic screen of rays direct from the tube with the penetrating power for the same screen of rays which have passed through a screen of some other metal. The ratios of transmission were used as a basis of comparison. With most metals it was found to be true that the ratio of transmission for a given screen was greater when the rays

had passed through a screen of another metal than when they came direct from the tube; in the language of the subject, the rays were "hardened" by passage through the first screen. The following ratios of transmission show this:

Copper alone,	0.587	Copper behind silver,	0.608
Aluminium alone,	0.875	Aluminium behind tin,	0.928
Aluminium alone,	0.85	Aluminium behind copper,	0.91
Copper alone,	0.53	Copper behind tin,	0.65

TABLE VIII.

EFFECT OF TRANSMISSION THROUGH SILVER ON PENETRATING POWER FOR ALUMINIUM.

Throw, cms., no Screen.	Throw, cms., Al. Screen.	Ratio.	Throw, cms., Ag. Screen.	Throw, cms., Ag.-Al. Screen.	Ratio.
2.02					
	1.69	0.84			
2.02					
			1.25		
				1.05	0.85
			1.21		
1.79					
	1.54	0.81			
1.74					
			1.15		
				0.96	0.88
			1.15		
1.83					
	1.59	0.85			
1.90					
			1.24		
				1.07	0.86
			1.23		
1.91					
	1.71	0.89			
1.95					
			1.29		
				1.13	0.88
			1.28		
2.06					
	1.76	0.87			
1.98					
Means		0.852	. . . . .		0.855

In these experiments the thicknesses of the various screens were: copper, 0.0044 cm.; silver, 0.0019 cm.; aluminium, 0.027 cm.; tin,

0.0012 cm. When the first screen was of silver, however, and the screen for which the penetrating power was being investigated was of aluminium, the data in Table VIII were obtained. According to

TABLE IX.

EFFECT OF TRANSMISSION THROUGH ALUMINIUM ON PENETRATING POWER FOR SILVER.

Throw, cms., no Screen.	Throw, cms., Ag. Screen.	Ratio.	Throw, cms., Al. Screen.	Throw, cms., Al.-Ag. Screen.	Ratio.
2.22	1.43	0.65			
2.18			1.67	1.04	0.63
			1.65		
2.08	1.28	0.65			
1.86			1.30	0.78	0.59
			1.33		
1.57	1.00	0.63			
1.60			1.18	0.73	0.63
			1.14		
1.48	0.96	0.65			
1.46			1.12	0.70	0.62
			1.13		
1.42	0.92	0.65			
1.41			1.06	0.68	0.64
			1.07		
1.35	0.87	0.65			
1.30					
Means . . .		0.647	. . . .	. . . . .	0.622

these measurements, the effect of transmission through silver on absorption by aluminium is very small. A slight modification of this experiment, performed some days later, gave a more striking result, as shown in Table IX. "Ag.-Al. Screen" indicates that the rays trav-

ersed first the silver screen, then the aluminium, and *vice versa*. From the latter measurements it would appear that the effect of transmission through aluminium is actually to "soften" the rays for silver. With no other pair of metals was this anomalous effect observed, and even with this pair it was not always obtained, but depended much on the state of the tube. An experiment performed only a few minutes before the one showing the "softening" effect gave a quite different result, but the change in the condition of the tube between the two experiments was evident to the eye. Direct experiments showed that the secondary radiation diffused from the screens cannot account for the observed effect.

5. *Effect of the Order of the Pieces in a Two-Piece Screen upon Transmission through the Screen.*

In order to throw some light on the nature of the phenomena which are involved in transmission, the following set of experiments was devised :

A screen was made by placing face to face two pieces of different metals, and the deflection obtained from the rays transmitted by this screen was compared with that obtained when the order of the two pieces of metal in the screen was reversed. In practice it was found convenient to prepare two screens, one composed of two metals in one order and the other composed of the same metals in the other order, and to compare the deflections accompanying the interposition of the two screens in succession. In using this method it had to be shown by an auxiliary experiment that there was no difference in the thickness of the two pieces of either metal, which might produce a spurious effect or mask a real one. This test was usually applied by reversing, in each screen, the order of the pieces of metal composing it. In all of the experiments the deflections were standardized in the manner before described, by comparison with deflections obtained when no screen was interposed. In some of the experiments the three-seconds exposure was used, and in others the rays were allowed to run until the greatest attainable deflection was reached. The quality of the rays used in the different experiments varied over a wide range, and sometimes it was allowed to vary considerably during a single experiment, as was the case in the example given in Table X. Copper and silver were the two metals used in this experiment. The copper was 0.0044 cm. thick, and the silver 0.0019 cm. After reversing the order of the plates in each screen, the data summarized in Table XI were obtained.

From these measurements it appears that the order of the pieces

in a two-piece screen of silver and copper does not affect the transmission appreciably. This conclusion evidently holds for a considerable range of quality of the incident radiation, as the parallel variations of values in the two columns of ratios in Table X indicate.

TABLE X.

EFFECT OF REVERSING THE ORDER OF THE METALS IN A TWO-PIECE SCREEN.

Throw, cms., no Screen.	Throw, cms., Silver-Copper Screen.	Ratio.	Throw, cms., Copper-Silver Screen.	Ratio.
4.32				
	1.55	0.36		
4.19				
			1.62	0.38
4.43				
	1.66	0.38		
4.28				
			1.79	0.41
4.56				
	1.85	0.40		
4.67				
			1.86	0.39
4.76				
	1.90	0.39		
4.89				
			2.02	0.41
4.89				
	2.05	0.42		
4.88				
			2.04	0.41
4.95				
	2.02	0.41		
4.92				
			2.20	0.44
4.97				
	2.20	0.45		
4.84				
			2.20	0.46
4.76				
	2.21	0.46		
4.89				
			2.28	0.46
4.92				
	2.17	0.45		
4.73				

Similar conclusions were deduced from experiments on other pairs of metals. The four metals, copper, silver, aluminium, and tin, were taken two by two in each of the six possible ways, and in every case it was found that the ratio of transmission for the two-piece screen was independent of the order of the pieces, within the experimental error.

The means of the ratios of transmission for each pair of metals follow:

Copper-aluminium, 0.424	Aluminium-copper, 0.430
Tin-aluminium, 0.567	Aluminium-tin, 0.560
Aluminium-silver, 0.489	Silver-aluminium, 0.489
Copper-tin, 0.336	Tin-copper, 0.331
Tin-silver, 0.368	Silver-tin, 0.365

The thicknesses used were: Copper, 0.0044 cm.
Tin, 0.0012 cm.
Silver, 0.0019 cm.
Aluminium, 0.050 cm.

TABLE XI.

CHECK ON CORRECTNESS OF PROCEDURE IN EXPERIMENT OF TABLE X.

Ratio of Transmission Copper-Silver Screen.	Ratio of Transmission Silver-Copper Screen.
0.47	0.47
0.47	0.47
0.48	0.48
0.47	0.47
	0.48

V. DISCUSSION OF EXPERIMENTAL RESULTS.

The qualitative law which connects the thickness of a screen with the transmission through it, as stated and illustrated on pages 680, 681, was first enunciated by Röntgen.[16] He explained the phenomenon by assuming that the beam emitted by the tube consists of a mixture of different kinds of rays, some of which have more penetrating power than others. If such a beam were passed through a plate of any substance, the less penetrating rays would suffer absorption to a greater extent than the more penetrating ones, and the penetrating power of the emergent beam would be on the whole greater than that of the original beam. This explanation is a satisfactory one so far as

[16] W. C. Röntgen, Ann. d. Phys., **64**, 18 (1898).

the phenomena observed with different thicknesses of one metal are concerned.

Another explanation of the phenomena of transmission has recently been proposed by Walter.[17] His theory assumes that the effect of transmission through any substance upon a beam of rays, which may be supposed homogeneous, is essentially a transformation of the character of the beam, — a transformation which in some way renders the rays more penetrating toward all substances. In particular, transmission through a piece of silver, cadmium, or tin is assumed to render the rays especially penetrating toward another piece of either of those metals, and the more so as the atomic weights of the two metals concerned are more nearly equal. These assumptions are a necessary consequence of his experimental results, which are briefly as follows: The penetrating power of the rays direct from the tube was compared with the penetrating power of the rays after transmission through a sheet of silver. The comparison was made by the use of the Benoist-Walter scale of hardness[18] and a photographic plate. It appeared that the rays were rendered less penetrating by transmission through the silver. Transmission through cadmium and through tin showed the same effect to a less extent. The effect of transmission through each of the three metals was also examined by means of scales of hardness in which the central disk of silver was replaced by one of cadmium or by one of tin; in every case it was found that the greatest reduction of penetrating power occurred when the central disk of the scale was of the same metal as the interposed sheet, and that this reduction of penetrating power diminished as the atomic weight of the metal of the disk departed from that of the metal of the interposed sheet. Transmission through sheets of metals other than silver, cadmium, or tin appeared in all cases to increase the penetrating power of the rays as measured by either of the three scales of hardness. A different series of experiments with the fluoroscope indicated that the anomalous reduction of penetrating power by transmission through silver, cadmium, or tin was apparent rather than real, and that in every case the effect of transmission through one metal was to increase the penetrating power of the rays for every metal. This result, if correct, makes untenable an hypothesis of relative selectivity in the absorption of the rays by different metals, which otherwise might explain the experiments with the scales of hardness, and renders necessary some such theory as the one which Walter proposes.

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[17] B. Walter, Ann. d. Phys., **17**, 561 (1905).

[18] B. Walter, loc. cit.

The experiments of the present research upon the effect of transmission through one metal on penetrating power for another were undertaken for the purpose of confirming or disproving the *necessity* of such a theory of transformation. The results which are summarized on page 688 are in agreement with the general statement which Walter has deduced from his fluoroscopic work, so far as they go; but the result of the experiments with silver and aluminium, given on page 690, is contradictory to that statement, and indicates that relatively selective absorption among metals may exist.

In view of the doubt thus cast upon the *necessity* of a theory of transformation, direct experimental evidence of transformation was sought by means of measurements of transmission through a screen composed of two pieces of different metals. These measurements are described on pages 691, 692. It is to be expected that if transformation occurs in the metals, the effect of the second metal upon rays transformed by the first will not be quantitatively the same as the effect of the first metal upon rays transformed by the second. In other words, the transformation theory leads us to expect that the ratio of transmission of a two-piece screen will depend upon the order of the pieces; and the absence of this dependence, experimentally shown, is evidence of the absence of transformation.

With the possibility of transformation in transmission thus removed, and with experimental evidence [19] showing that any effect of the surfaces of the metal upon transmission is small, the only conceivable action produced upon a beam of rays by transmission through a metallic screen is an absorbing action. To explain the phenomenon observed by Röntgen with different thicknesses of the same metal, we must suppose, with him, that the rays from a tube are heterogeneous, and that different kinds of rays are differently absorbed in any one metal. To explain Walter's apparent reduction of penetrating power by transmission in certain cases, we must suppose that rays which are more penetrating for some metals are less penetrating for others, — that is, that metals show relatively selective absorption, and that the apparent reduction of penetrating power by transmission through silver, etc., is a real reduction of penetrating power with respect to aluminium. In judging of the significance of Walter's fluoroscopic work, as in fact of all work on Röntgen rays, it must be borne in mind that the selectivity of the absorbing media of the instruments themselves must greatly affect the magnitude of their indications, and that an exact interpretation of those indications is

[19] See Tables V–VII and Figure 5.

beyond our knowledge at present. This consideration will explain many disagreements in the results obtained by observers using different instruments.

It is simplest to suppose that the effect of transmission through a metallic screen upon any one component of a heterogeneous beam is independent of the presence or absence of the other components. In other words, the effect of a given screen upon the transmission of a particular sort of ray is measured by an absorption coefficient which may change with the conditions of the experiment only in so far as those conditions affect the ray in question. An attempt has been made to test the constancy of these coefficients under changing intensity of the rays, by the experiments where the dependence of the ratio of transmission upon the distance between the tube and the screen was investigated. These experiments are given in detail on pages 682, 683.

It seems very probable that in experiments so conducted the variation in the intensity of the rays incident on the screen, involved in moving the tube, very nearly fulfils the condition that the changes in the intensities of all the components of the beam shall be in one ratio. Except for the absorption by the air, this ratio is doubtless fixed for all the different sorts of rays by some function of the distances involved; and from numerous experiments with various instruments [20] it appears that the absorption by air of Röntgen rays in general is negligible for such short distances as these. Of course a real disturbing factor is the changing behavior of the tube, for which correction is made, as well as possible, by alternating and checking readings. Granting that these sources of error have had no appreciable effect, we learn from the observations that the ratios of transmission of the metallic screens examined are independent of the total intensity of the incident radiation, when that intensity changes in such a way that the intensities of all the components change in the same ratio.

If we examine this result in the light of the conclusions already reached in this paper, its practical importance will appear. It is plain that if we knew in advance that all of the absorption coefficients for the metallic screen and the beam in question are constant so far as the intensity is concerned, the constancy of the ratio of transmission would necessarily follow, provided we conclude from the data of Table IV that all of the absorption coefficients of platinum are independent of the

[20] J. Trowbridge and J. E. Burbank, Amer. Jour. Sci., **157**, 396 (1899); A. M. Mayer, Amer. Jour. Sci., **151**, 467 (1896); C. G. Barkla, Phil. Mag., **7**, 555 (1904).

intensity. But to draw conclusions as to the constancy of any or all of the separate coefficients from the constancy of the ratio of transmission is not in strictness possible. It might be that two or more of the coefficients changed together in such a way as to keep the ratio of transmission constant. But the repetition of this coincidence in experiments with different metals and with rays from tubes in very different conditions is exceedingly unlikely, and the constancy of the ratio of transmission with varying intensity is at least very good presumptive evidence that the coefficients characteristic of the absorption of Röntgen rays in metallic sheets are all constant with varying intensity of the rays. It may be of interest to examine the consequences of supposing that the constancy of the ratio of transmission is not a result of the constancy of each of the coefficients. To simplify the argument, let us suppose that the metallic screen is very near the instrument. Let s_1 and s_2 represent respectively the fraction of a certain sort of ray which the metallic screen transmits at the large intensity and at the small intensity. Let p be the fraction of the same sort of ray which the platinum of the instrument transmits at all intensities. Let I_1 and I_2 represent the two intensities of this sort of ray at the instrument. Then the ratio of transmission for this ray alone at the large intensity would be

$$\frac{I_1 s_1 (1 - p)}{I_1 (1 - p)},$$

or s_1; and at the small intensity,

$$\frac{I_2 s_2 (1 - p)}{I_2 (1 - p)},$$

or s_2. If the ratios of transmission for the whole beam are found to be the same at the two intensities, the explanation must be either that each s_1 is equal to its corresponding s_2, or that some of the s_1's are larger than their corresponding s_2's while others are smaller. The latter explanation is equivalent to saying that the absorption coefficients for some sorts of rays are increasing functions of the intensity, while others are decreasing functions; and this seems highly improbable.

The argument of this section may be summarized in another form, as follows:

The possible effects of transmission through a metallic screen upon a beam of Röntgen rays are three:

(1) An effect produced upon the beam by transmission across the surfaces of the screen.

(2) An effect of *transformation* suffered by the several components of the beam in passing through the substance of the screen.

(3) An effect of *absorption* suffered by the several components of the beam in passing through the substance of the screen.

Experimental results rule out, more or less certainly, the first two effects. Granting these results, a theory of relatively selective absorption is necessary to explain the reduction of penetrating power for one metal by transmission through another. By somewhat indirect experimental evidence, this absorption is shown to be governed by coefficients which are probably constant with varying intensity of the rays.

VI. Conclusions.

The following conclusions are reached in this paper:

(1) The approximate measurement of the energy of Röntgen rays is of the same order of magnitude as the earlier measurements of that energy, and to that extent confirms them.

(2) In the transmission of Röntgen rays through metallic sheets, the effect of the surfaces of the metal is small.

(3) In the transmission of Röntgen rays through metallic sheets, the probability that one sort of ray is transformed into another sort of ray, to an appreciable extent, is small.

(4) The absorption of any particular sort of ray by a metallic sheet is measured by a coefficient which is probably independent of the intensity of that ray.

(5) In one special case, at least, the general effect on absorption by one metal of passing the rays through another metal is not, so far as we can judge, a decrease of absorption, but an increase; and this fact tends to support the theory that the radiation from an ordinary tube is heterogeneous in character, and that the absorption in metallic sheets is more or less selective.

It is hoped to continue this research in the direction suggested by the conclusions of this paper: to test the hypothesis of relatively selective absorption by direct experiment;[21] to obtain, if possible, beams of Röntgen rays which will yield transmission curves of a simpler form than those heretofore found; to study the properties of those beams; and to study the indications of the instrument used in this research in comparison with those of other instruments heretofore used, especially the ionization-electroscope and the photographic plate.

[21] For a preliminary note on this experiment, see Amer. Jour. Sci., **173**, 91 (1907).